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NON-FERROUS SLAGS FROM CANADIAN SOURCES
PART II - PROPERTIES AND STRENGTH DEVELOPMENT

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NON-FERROUS SLAGS FROM CANADIAN SOURCES
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by

E. Douglas and V.M. Malhotra

SUMMARY

This report reviews critically the available information on the cementitious properties and utilization of non-ferrous slags as a first step in a study directed to identify copper, nickel and lead slags from Canadian sources which have a potential for use as cement replacement.

Methods for determining glass content in non-ferrous slags are reviewed. Pozzolanic activity and strength development of portland cement slag binders are discussed.

It is concluded that non-ferrous slags appear to have considerable potential for portland cement replacement in cemented mine backfill and in concrete.

RESUME

On présente une révision critique de l'information disponible sur les propriétés liantes et l'utilisation des laitiers non-ferreux. Ceci sert d'introduction à une étude qui a pour but l'identification des laitiers de cuivre, de nickel et de plomb d'origine canadienne capables de substituer le ciment portland dans des liants hydrauliques. Les méthodes pour déterminer le degré de vitrification sont passées en revue. L'activité pouzzolanique ainsi que le développement de résistance à la compression de mortiers contenant des laitiers non-ferreux sont examinés. On arrive à la conclusion que les laitiers non-ferreux peuvent être avantageusement utilisés comme agents de substitution partiel du ciment portland dans la fabrication du béton ainsi que dans les opérations de remblai dans l'industrie minière.

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INTRODUCTION

In the past the byproducts of metallurgical processes were traditionally discarded in waste dumps in North America. Over the last decade those by-products became increasingly recognized as residuals of production processes in which significant energy had been invested and lost through disposal. Considerations related to energy costs and the environment created the need for waste management strategies to conserve materials and reduce energy consumption through recovery, regeneration, recycling or utilization of industrial wastes, especially in the cement, foundry, non-ferrous and ferroalloy industries (1, 2). Studies on the key areas of energy loss in the iron and steel industry, for example, revealed a 29 to 44 per cent loss in the generation of hot materials like slag, coke and slabs (3).

Higher energy costs in conjunction with the increasing pressure exerted by concerned environmentalists prompted research work that led to the recovery of a significant fraction of the energy invested in blast furnace slag. Vitrification and grinding of the blast furnace slag produced a material that could be added at the mixer as cement replacement in concrete manufacturing (4). The use of ground blast furnace slag in construction work represents an energy saving of about 5000 MJ per metric ton when compared to the energy required to produce the same amount of portland cement by the wet process (5), or the saving of 0.8 barrels of oil for every metric ton of portland cement replaced by ground blast furnace slag (6). In Canada, vitreous (pelletized) iron blast furnace slag is produced at a rate of 2.2×10^5 t/a in Hamilton, Ont., of which approximately 45 per cent is used in concrete manufacture (7). Non-ferrous slags are produced in Canada in amounts that also warrant serious consideration. Approximately 4.1×10^6 t of copper, nickel and lead slags are produced annually, most of which is used as railroad ballast or disposed of in waste dumps (8). Successful utilization of the pozzolanic properties of granulated copper slag in cemented mine backfill operations in Australia (9, 10) and laboratory test results reported in a Canadian patent (11) warrant a study for the characterization of non-ferrous slags from Canadian sources for possible cement replacement in the mining and the concrete industries. The study could open the possibility of significant savings by reducing the volume of cement used as well as reduce costly

transportation of cement to remote areas. In Canada the production of copper, nickel, lead and lead-zinc slags added to the unused product of past activity has resulted in a total accumulation of over 17 x 10^6 tonnes (7). Most of the slags are produced in the provinces of New Brunswick, Quebec, Ontario, Manitoba and British Columbia where they are either used locally as railroad ballast or granular base fill in road construction (Fig. 1), or are accumulated in waste dumps. Potential utilization of non-ferrous slags could be found in a wide range of applications such as aggregate in concrete, binder for base stabilization, cemented mine backfill and cement replacement in concrete.

This report reviews critically the available information on the cementitious properties and utilization of non-ferrous slags as a first step in a study directed to identify copper, nickel and lead slags from Canadian sources which have a potential for use as cement replacement.

CHEMICAL COMPOSITION, GLASS CONTENT AND GRINDABILITY

Non-ferrous slags can be utilized as partial cement replacement if pozzolanic activity takes place in the presence of the $Ca(OH)_2$ originated in the hydration of the cement itself (12). The pozzolanic properties of the slags are controlled by their chemical composition, glass content and fineness (10, 11, 12) whether they are mixed with lime or cement. Similarly to blast furnace slag, setting time and strength development are likely to be affected by the action of alkali or sulphate activators (12) although limited results on studies in this area have been reported in the literature (11).

CHEMICAL COMPOSITION

Some information on the chemical composition of Canadian non-ferrous slags can be found in the literature (8, 11). Recent studies report the chemical composition of copper, nickel, and lead slags available in New Brunswick, Quebec and Ontario (Table 1) (13).

GLASS CONTENT

Early data have been published on the glass content of non-ferrous slags from Canadian sources such as a nickel-copper electric furnace slag granulated by quick quenching which glass content was measured by X-ray diffraction (14). The slag was too opaque for a reliable glass count by the optical method using polarizing light, similar to that adopted for quality control of iron blast furnace slag (15). The glass content reported was 95 per cent (16). Measurements of glass content by a method that uses SEM and image analysis were reported in a study on the hydration and the pozzolanic activity of ambient cooled and of quenched copper reverberatory slags from Northern Quebec (17) (Table 2). The results did not agree with those published by Roper et al. (18) who estimated a ratio of amorphous to crystalline material of approximately 1:1 in a quenched copper reverberatory slag. In the investigation with SEM and an image analyser the composition of the glass phase was determined with an electron microprobe (17) (Table 3).

GRINDABILITY

Research carried out on portland cement-slag mixes confirms the empirical notion that fineness modifies the rate of the hydration reactions, hence the mechanical resistance of hydraulic binders (12).

Information on grindability, energy requirements for grinding and particle size distribution of ground non-ferrous slags is limited. Laneuville (11) reported the estimated power required to grind to various fineness air-cooled and granulated nickel slags based on the duration of the grinds (Table 4). The particle-size distribution of a nickel-copper electric furnace slag, ground to a specific surface of 3,000 cm^2/g, was reported by McGuire (14) (Table 5). Size distribution of ground nickel slags from the Copper Cliff area tested for pozzolanic activity (19) is shown in Table 6.

A comparison between the energy required to grind portland cement clinker mixed with a 3 per cent gypsum and that required to grind Canadian air-cooled and quenched non-ferrous slags has been reported recently (13) (Fig. 2).

POZZOLANIC ACTIVITY OF NON-FERROUS SLAGS BINDERS

Pozzolanic materials contain fine, active silica which reacts with lime and water to form stable cementitious hydrated calcium silicates. Materials with proven pozzolanic activity which make them suitable for hydraulic cemented fill in mining operations are fly ash, ground quenched copper reverberatory furnace slag and ground blast furnace slag (20). According to Thomas (20), there are three aspects of the advantage of using pozzolanic materials in hydraulic fill to be considered:

1) reaction causing removal of lime, a material with potentially adverse effects,
2) production of a stronger cement due to removal of lime, allowing strength development at a lower portland cement content, and
3) formation of additional cementing materials from the pozzolanic reaction, resulting in equivalent strength at lower portland cement content.

Experimental evidence of this approach was found in the results of a study on the pozzolanic properties of a granulated copper reverberatory furnace slag which showed no obvious alteration after many years of being in a surface dump (9). The particle size analysis revealed essentially one component, approximating 2.54 mm in diameter. Test specimens were prepared from pulped mixtures of fill, portland cement and the slag ground to a specific surface of 3000 cm^2/g. The chemical composition of the slag used is shown in Table 7. Strength increases at increasing slag additions at fixed cement contents are shown in Fig. 3. These results were considered significant concerning cost reductions in cemented fill production with no strength loss, encouraging further research.

The same slag was tested at a later date in cemented mine fill at high slag/cement ratios (10). The fill contained 80 to 99 wt per cent of deslimed Isa Mine copper sulphide tailings, 1 to 5 wt per cent portland cement and 0 to 16 wt per cent slag (Fig. 4). It was concluded that slag additions, indicated as non-beneficial at 1 wt per cent portland cement, were consistently beneficial at 3 wt per cent portland cement and above, and transitional in effect at 2 wt per cent portland cement.

Pozzolanic activity tests by various methods (22) were carried out in Spain on a granulated copper slag. The results of the ASTM C-618-73 method showed strength above 75 per cent of the control specimens (Table 8).

Laneuville (11) determined the pozzolanic activity of air-cooled and of granulated nickel slags by the ASTM 595 method and reported that compressive strengths higher than the minimum 5.5 MPa set out in the specification were obtained with these slags ground to a specific surface in the range of 3,800 to 4,000 cm^2/g.

In Canada, strength gains with increasing contents of a granulated nickel-copper electric furnace slag were measured (14) in mixes containing 6 wt per cent of portland cement and a tailing fill of 2.96 relative density (Fig. 5). The strength gains were attributed to chemical bonding, typical in the hydration of a pozzolanic slag.

EFFECT OF GLASS CONTENT ON POZZOLANIC ACTIVITY

The effect of glass content on the pozzolanic properties of non-ferrous slags can be assessed by comparing strength development data of air-cooled and of water quenched slags (11, 12).

Pozzolanic activity tests of binders for mine backfill were performed in Canada (21) with air-cooled and with quenched nickel and copper-nickel slags at different cement replacement levels. The chemical composition of the slags tested and the mixture proportions of the cemented backfill from which the test specimens were cast are shown in Tables 9 and 10. Glass content of the air-cooled nickel reverberatory slag was estimated at less than 20 per cent. The change in compressive strength was calculated on the basis of a standard incorporating 4.8 wt per cent of portland cement (Fig. 6). Maximum changes in strengths were observed at 14 days for a sample incorporating 60 per cent of air-cooled nickel slag (21). Better performance in long-term curing of test specimens of a mix incorporating an air-cooled copper-nickel slag, as compared with the same water-quenched sample, in a mix containing 4.8 per cent cement, 1.2 per cent slag and 96 per cent tailings was not well understood.

Results reported on recent studies of pozzolanic activity of Canadian air-cooled and of quenched non-ferrous slags (13, 17) lead to the conclusion that, contrary to results of studies on blast furnace slag, for non-ferrous slags glass content and pozzolanic activity are not directly related. Test specimens of mortars with 35 and 70 per cent cement

replacement were prepared according to ASTM C-595 but cured at room temperature (17). The results of the pozzolanic activity studies show that air-cooled copper slags could outperform or at least equal the performance of quenched copper slags, depending on the fineness (Table 11). Similar results were reported on pozzolanic tests carried out on nickel, copper and lead slags according to ASTM C-595 (13). Pozzolanic and slag activity indexes are shown in Table 12.

EFFECT OF FINENESS ON POZZOLANIC ACTIVITY

Laneuville (11) evaluated the relative strength of mortars prepared according to ASTM C-109 where 30 per cent of the cement was replaced by air-cooled nickel slag ground at different fineness. The strength of the test specimens were compared to that of a portland cement mortar at various ages (Table 13). Laneuville (11) also studied the effect of fineness on the hydraulic index at different curing ages (Fig. 7). The effect of fineness on the pozzolanic activity of Canadian copper, nickel and lead slags, for air-cooled and for quenched samples, can be evaluated from the results reported in Tables 11 and 12.

STRENGTH DEVELOPMENT OF NON-FERROUS SLAGS BINDERS

Commercial utilization of ground non-ferrous slags for cement replacement in concrete has not developed in Canada as yet, mainly for lack of knowledge of their characteristics and limited data on their pozzolanic properties.

Most of the studies intended to encourage the use of copper, nickel and lead slags have been directed to explore the feasibility of their use as cement replacement in cemented mine backfill. Strength development of copper reverberatory furnace slag, dezinced lead smelter slag and copper converter slag in cemented fill were first studied by Thomas in Australia (Fig. 4 and 5) (9, 10). In connection with the investigation of new mining techniques, research on non-ferrous slags from Canadian sources is under way and plans for production tests have been made (21). Tests for strength development on mortars of non-ferrous slag binders were done by Laneuville (11) and by Baragano (22) using nickel and copper slags. Reports of research on the use of lead slags, as partial replacement in steam-cured

blocks have been published recently (24). The specimens were made with ground lead slags and calcium-bearing materials such as lime, gypsum and portland cement. Mixtures were prepared consisting of 3 parts of sand and 1 part of a binder formed by different combinations of Type III portland cement and a lead slag ground to 2,500 cm^2/g. The results showed that up to 25 wt per cent ground slag can replace cement before significant strength loss occurs (Fig. 8).

EFFECT OF GLASS CONTENT ON STRENGTH DEVELOPMENT

Limited information is available on the relationship between glass content and strength development with time in mortars of non-ferrous slag-cement mixes. Determination of glass content in non-ferrous slags by optical methods using polarized light has been reported inadequate because of the opaque nature of the slag particles (13). Recent studies carried out on Canadian non-ferrous slags report the determination of glass content in the slags by image analysis methods using micrographs from the SEM and an image analyser (17). Representative micrographs of fields about 300 x 300 micrometres and 60 x 60 micrometres were produced on the SEM from each slag sample. These were then used as input to the image analyser. During this analysis, crytals smaller than about 1 micrometre in maximum dimension were counted as glass since discrimination is difficult in this size range. Hence, the measured quantities of crystals represent minimum values. Approximately 15 fields were traversed on each of 6 SEM micrographs and the counts averaged for each phase, glass, fayalite, spinel or sulphide. Other techniques, such as quantitative X-ray diffractometry and polarizing optical microscopy were used to determine the proportion of glass in the same slags (15). It was found that the X-ray diffraction technique was not adequate for quantitatively determining glass content in the slags. The optical method, using ground slag and a polarizing petrographic microscope, was limited by the fine grain size of crystals which could not be resolved by the optical microscope.

Results on strength development of air-cooled and of quenched non-ferrous slags binders were reported in a Canadian patent (11). Mortars made with 70:30 cement to slag ratio were tested for compressive strength (ASTM C-109). Air-cooled and granulated nickel slags ground to a specific surface of 4,000 and 3,800 cm^2/g, respectively, were used. Results to 90 days of curing indicated that water quenching improved long-term strength

of nickel slag binders (Fig. 9).

Nevertheless, results of studies on the compressive strength of air-cooled and of water-quenched nickel slags in mixes of mine tailings with 4.5 wt per cent cement (21) showed better performance of an air-cooled slag as compared with the corresponding water-quenched sample (Fig. 10).

Tests on strength development of mortars (C-109) of air-cooled, granulated and quenched lead, nickel and copper slags from Canadian sources have been recently reported (Table 14) (13). Portland cement in the mortar was replaced by the slags at different replacement levels. The mortars were cured at 38°C for 28 days. Higher strengths were observed in air-cooled than in quenched nickel slags. Strengths of granulated copper slag from the province of Ontario were slightly improved by adding 20 per cent CaO to the melted slag and quenching in excess water. Air-cooled copper reverberatory furnace slag from the province of Quebec exhibited higher strengths than the quenched slag from the same source in some of the specimens.

Another series of tests were performed with mortars (C-109) in which 50 per cent of the portland cement was replaced by the slag. The mortars were cured at room temperature (23°C) and tested at 1, 7, 28 and 90 days (Table 15).

Strength development in mortars of portland cement-copper slags binders with 35 and with 70 per cent cement replacement was recently reported (17). The mortars (ASTM C-595) were placed in close fitting containers stored at 23 ± 1.7°C and tested at 1, 7, 28 and 90 days (Fig. 11).

The compressive strength of mortar incorporating 35 per cent of air-cooled slag ground to 4000 cm^2/g (Blaine method) was higher than that of a mortar incorporating 35 per cent of the quenched slag. At 90 days the strength of the former attained that of the portland cement mortar used as control. In mortars with 70 per cent replacement the mortar incorporating the quenched slags developed higher strength than that incorporating the air-cooled slag.

EFFECT OF FINENESS ON STRENGTH DEVELOPMENT

Improved strengths of finer granulated blast-furnace slags reported in the literature (24) led some investigators to study the effect of fineness in strength development of nickel slag binders (11). Compressive strength

tests were done using mortar (ASTM C-109) containing 70 per cent portland cement and 30 per cent air-cooled nickel slag. The mortars were cured in water at 23°C. An increase of approximately 15 per cent in compressive strength after 90 days was observed for specimens made with slags ground to 4000 cm^2/g as compared to those slags ground to 3000 cm^2/g (Fig. 12). Mortars were also made with an air-cooled nickel slag of similar chemical composition but with a MgO content 2 per cent higher than in the first sample. Strength development of the two air-cooled slags was approximately the same when ground to a specific surface of 4000 cm^2/g. Increasing the specific surface to 7700 cm^2/g resulted in approximately 15 per cent increase of compressive strength at 90 days. Compressive strengths at 28 days of mortars incorporating lead, nickel or copper slags ground to 2000, 3000, 4000 and 5000 cm^3/g are given in Tables 14 and 15 (13). Strength development of mortars incorporating copper reverberatory furnace slag ground at different fineness and cured at 23°C are shown in Fig. 11 (17).

EFFECT OF SLAG CONTENT ON STRENGTH DEVELOPMENT

Apparent discrepancies have been reported on the effect of slag content on strength development of nickel slag binders. Thomas (25) found increasing strength in mixes of tailings with a fixed amount of portland cement and copper slag content close to double that of cement. Laneuville (26) reported negligible contribution of a granulated nickel slag to early age strength and a progressively greater contribution after 90 days of wet curing at 21°C for binders containing less than 45 per cent slag (Fig. 13). The discrepancy between the two sets of results, those of Thomas and of Laneuville, was explained by Laneuville in terms of the decreasing ratio of water to cementitious materials when larger amounts of slag are added to a constant amount of portland cement. Measurements of the combined water in mortars of slag binders showed the direct relationship between compressive strength and the water bound to the hydration products (Fig. 14). In cemented fills, the contribution of the addition of a nickel-copper slag to hydration products, i.e., to compressive strength, have been found significant (14) (Fig. 15).

EFFECT OF ACTIVATORS ON STRENGTH DEVELOPMENT

Low compressive strength values at early ages obtained in mortars with 65:35 portland cement to copper slag ratio led to the study of the effect of alkaline activators on early strength (22). Five to ten per cent precipitator dust with an alkali oxide content of approximately 5 per cent was added to mortars made with portland cement and copper slag blends. Up to 25 per cent increase in compressive strengths at 7 days was observed.

The effect of calcium carbonate and calcium chloride on air-cooled and on granulated nickel slag was investigated by Laneuville (11) in mortars with 30 per cent portland cement replacement. It was concluded that the compressive strength of nickel slag mortars is not improved by increasing its basicity. Activation with calcium chloride was found effective for improving air-cooled slags performance after 7 days curing (Fig. 16). The results reported showed improvement of strength at all ages in granulated slags with addition of 2 per cent calcium chloride.

Tests done on compressive strengths of mine backfill with addition of activators such as calcium chloride, lime water or limestone spiked in quenched slag are not conclusive (19, 20), especially concerning long-term performance.

Laneuville (11) tested the effectiveness of precipitator dust used as an activator. The kiln dust contained 16.8 per cent potassium oxide and 9.5 per cent free calcium oxide. It was concluded that the incorporation of cement precipitator kiln dust into portland cement-nickel slag binders yielded binders with improved early strength characteristics and properties close to those of portland cement mortars. CANMET studies indicated that activation of lead, nickel and copper slags by addition of Na(OH) (200 g/L) to the mixing water in mortars or by replacing cement by cement kiln dust in the mortar has been unsuccessful (13).

DURABILITY OF MORTARS INCORPORATING NON-FERROUS SLAGS

The performance of concrete with partial replacement of cement by non-ferrous slags possessing pozzolanic properties is not known. In mortars, Baragano (22) reported results of tests on the protective capacity against corrosion for steel reinforcement. Good results were observed for copper slag-cement blends without addition of $CaCl^2$ as activator.

Tests for resistance to sulphate attack were also done on mortars with copper slag-portland cement blends (22). Calcium, magnesium and sodium sulphate solutions as well as sea water were used as aggressive agents. Greatest resistance was shown by a slag cement with 35 per cent copper slag as compared with portland cement mortar or with portland cement blended with 35 per cent natural pozzolan. Similarly, a study on the behaviour in freeze-thawing cycles of the same mortars showed better performance of the copper slag as compared with the natural pozzolan.

CONCLUDING REMARKS

1. Non-ferrous slags appear to have considerable potential for portland cement replacement in cemented mine backfill and in concrete.

2. Considerable research work has to be done to define areas of application as well as limitations.

SUGGESTED RESEARCH

A research program directed to explore the feasibility of the use of non-ferrous slags should include:

1. development of standards for quality control,
2. development of tests for detection of potential health hazard due to leaching of deletereous elements,
3. tests for resistance of concrete to external agents (reinforcement corrosion, sulphate resistance, alkali-aggregate reaction).

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Table I – Chemical analysis of non-ferrous slags[a]

%	Lead (N.S.) Granulated	Nickel (Out.) Air-cooled	Nickel (Out.) Quenched	Copper (Out.) Granulated	Copper (Out.) Quenched	Copper (Que.) Air-cooled	Copper (Que.) Air-cooled	Copper (Que.) Quenched	Copper (Que.) Granulated
SiO_2	19.91	35.66	37.25	26.54	22.10	36.26	34.51	36.78	34.41
Al_2O_3	1.66	5.59	6.17	3.74	2.94	2.16	6.55	7.16	6.82
Fe_2O_3(1)	45.35	32.99	31.07	60.07	44.16	49.00	49.50	50.00	49.64
CaO	16.60	2.74	2.97	2.09	20.12	7.10	2.50	1.91	1.66
MgO	0.68	2.51	2.43	1.61	1.52	1.91	1.48	1.49	1.91
Na_2O	0.26	0.87	0.86	0.19	0.21	0.28	1.02	1.06	1.14
K_2O	0.25	0.65	0.62	0.11	0.98	1.26	1.01	0.96	0.66
TiO_2	0.14	0.32	0.31	0.14	0.12	0.11	0.15	0.19	0.28
MnO	0.09	0.07	0.07	0.10	0.08	0.08	0.10	0.09	0.08
S	-	-	-	1.10	-	0.48	0.41	0.41	0.48
Cu	-	0.21	0.25	-	-	-	-	-	-
Pb	4.84	-	-	-	-	-	-	-	-
LOI(2)	-5.75	-5.12	-6.00	-5.84	-4.19	-1.91	-5.24	-6.11	-4.71
	1.30	1.46	1.39	1.28	0.45	1.01	1.20	1.11	1.00

1) Total iron expressed as Fe_2O_3.
2) LOI at 700°C. Negative values indicate presence of FeO.
From Ref. 13.

Table 2 - Slag constituents determined by image analysis*

Sample	Fields	R**	Glass	Fayalite	Spinel	Sulphide
Air-cooled	30	1.5	41±4	57±6	5±1	0.2
Quenched	20	0.3-0.1	75-95	15-5	10-trace	---

*From Ref. (17)
**Ratio of crystals to glass

Table 3 - Compositions of glass determined by electron microprobe*

	Air-cooled Slag	Quenched Slag
MgO	---	1.4 ± 0.03
Al_2O_3	14.5 ± 0.2	10.1 ± 0.2
SiO_2	45.8 ± 0.8	38.6 ± 0.5
K_2O	2.1 ± 0.2	0.6 ± 0.03
CaO	3.6 ± 0.7	1.7 ± 0.04
MnO	0.1 ± 0.02	0.1 ± 0.03
Fe_2O_3**	28.7 ± 3.8	39.4 ± 0.6
ZnO	5.3 ± 0.7	5.0 ± 0.2
PbO	0.8 ± 0.1	0.4 ± 0.1
Total	100.9	101.4

*From Ref. (17)
**Total Fe calculated as Fe_2O_3

Table 4 - Estimated kWh/ton required to grind nickel slag, calculated from grinding times*

	Air-cooled #1	Air-cooled #2	Granulated
Fineness (cm^2/g, Blaine method)			
3000	50	58	88
3500	65	65	107
3800	77	77	117
4000	83	83	128

*From Ref. (11)

Table 5 - Particle-size distribution of nickel granulated slag ground to 3000 cm^2/g*

Particle Size (micrometres)	Weight Percentage	
	Slag	Fill
+208	0.5	9.5
+1147	0.5	17.2
+104	0.7	16.7
+ 74	2.4	16.3
+ 53	9.7	11.3
+ 38	10.7	15.9
+ 27	29.7	12.2
+ 19	9.7	0.4
+ 13	9.9	0.2
+ 9	6.9	0.1
+ 7	4.42	0.06
+ 5	4.97	0.05
+ 3	4.97	0.05
+ 2	3.38	0.03
- 2	1.36	0.01

*From Ref. (14)

Table 6 - Size distribution of ground slags tested for pozzolanic activity*

Microns	CC Dump**	
	Wt %	Cum Wt
+74	0.09	0.09
45	0.14	0.26
37	0.09	0.32
23	2.57	2.89
17	12.88	15.77
13	14.08	29.85
-13	70.15	100.00

Surface Area

Blaine (cm^2/g)	4437
B.E.T. (Gas Adsorption)	
m^2/g	20.9
Specific Gravity	3.30

**CC Dump slag stands for Copper Cliff dump slag.

* From Ref. (19).

Table 7 - Typical chemical composition of copper reverberatory furnace slag*

Item	Weight Percentage
Fe	36.0
SiO_2	35.5
CaO	7.9
Al_2O_3	3.6
MgO	1.9
S	0.9

*From Ref. (9)

Table 8 - Pozzolanic activity of copper slags*

	Cement Portland (A)	65% cement + 35% slag (B)
W/C	0.58	0.54
Flow %	1.05	1.05
28 days 56-370	kp/cm^2	44-285 kp/cm^2
	(B:A) 100 = 79-77 (75%)	

*From Ref. (22)

Table 9 - Chemical composition of air-cooled and of quenched nickel slags*

	Fe	S	SiO_2	CaO	MgO	Al_2O_3	$\%Al_2O_3+CaO+\%MgO/\%\ SiO_2$ Hydraulic Modulus
(1) Nickel reverberatory air cooled	36.0	1.5	35.5	2.25	2.50	5.05	0.2761
(2) Nickel reverberatory water quenched	35.8	1.4	36.8	2.30	2.45	5.55	0.2799
(3) Flash furnace slag air cooled	35.8	1.5	30.8	7.00	2.45	6.00	0.5016
(4) Flash furnace slag water quenched	34.4	1.4	31.0	7.05	2.50	6.50	0.5177
(5) Nickel reverb.+14% limestone water quenched	32.9	1.4	32.8	9.40	2.45	5.85	0.5396
(6) Ground quartz	0.58	---	87.7	0.27	0.029	1.10	0.0160

*From Ref. (21).

Table 10 - Composition of the specimens incorporating air-cooled and quenched nickel slags*

Series No.	1	2	3	4	5	6	7
Description	Standards						
Wt % Slag	0	0	1.2	4.5	4.5	8.7	16.0
Wt % Cement	9.1	4.8	4.7	4.6	4.5	4.4	4.0
Wt % Tailings	90.9	95.2	94.1	93.1	91.0	86.9	80.0
Total Wt % Binders	9.1	4.8	5.9	6.9	9.0	13.1	20.0
% Cement Replacement	0	0	20	33	50	66	80
Tails/Cement/ Slag	10:1:0	20:1:0	20:1:25	20:1:50	20:1:1	20:1:2	20:1:4

*From Ref. (21).

Table 11 - Pozzolanic and slag activity indexes of portland cement-slag mortars cured at room temperature*

PI/HI(2)	Copper Air-cooled	Copper Quenched
2000	0.71/0.32	0.67/0.31
3000	0.73/0.36	0.87/0.27
4000	0.89/0.49	0.85/0.70
5000	0.91/0.38	1.06/0.52

(2) PI:pozzolanic index; HI:slag activity index (hydraulic index).
*From Ref. (17).

Table 12 - Pozzolanic and hydraulic indexes of Canadian non-ferrous slags*

PI/HI	Lead (N.B.) Granulated	Nickel (Ont.) Air-cooled	Nickel (Ont.) Quenched	Copper (Ont.) Granulated	Copper (Ont.) Quenched	Copper (Que.) Air-cooled	Copper (Que.) Air-cooled	Copper (Que.) Quenched	Copper (Que.) Granulated
2000	0.50/0.25	0.64/0.40	0.55/0.26	0.48/0.24	0.57/0.33	0.49/0.24	0.58/0.39	0.51/0.32	0.56/0.32
3000	0.54/0.27	0.73/0.43	0.67/0.41	0.69/0.29	0.72/0.43	0.67/0.35	0.80/0.49	0.73/0.42	0.70/0.40
4000	0.96/0.29	0.83/0.58	0.78/0.44	0.69/0.31	0.76/0.45	0.70/0.47	0.85/0.59	0.80/0.54	0.79/0.50
5000	1.01/0.36	0.98/0.67	0.88/0.57	NG	0.81/0.52	0.83/0.53	1.02/0.71	0.85/0.69	0.83/0.64

NOTES:

1. Nominal Blaine fineness of slags indicated - 2000, 3000, 4000 and 5000.
2. NG indicates slag was not ground to this fineness.
3. PI and HI are the pozzolanic (pozzolanic activity index) and hydraulic (slag activity index) index with cement, respectively, in accordance with ASTM C595.

*From Ref. (13).

Table 13 - Relative strength of portland cement-nickel slag mortars showing the effect of fineness*

Slag Fineness (cm^2/g)	Curing Age (days)	Relative Strength (%)
3000	3	63
	7	66
	28	81
4000	3	60
	7	72
	28	78
7700	3	68
	7	75
	28	90

*From Ref. (11).

Table 14 - Compressive strength at 28 days of "C-109" mortar cubes cured at 38°C 20, 35, 50 and 70 per cent absolute replacement of portland cement

		Lead (N.B.) Granulated	Nickel (Ont.) Air-cooled	Nickel (Ont.) Quenched	Copper (Ont.) Granulated	Copper (Ont.) Quenched	Copper (Ont.) Air-cooled	Copper (Que.) Air-cooled	Copper (Que.) Quenched	Copper (Que.) Granulated
CONTROL		29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6	29.6
20%										
2000	MPa	21.4	22.5	17.1	16.0	20.7	20.8	21.7	19.3	20.2
3000		22.7	24.0	20.9	21.4	23.6	22.1	25.2	23.9	20.6
4000		30.5	24.8	21.8	25.4	25.8	24.6	26.5	25.7	24.6
5000		32.1	30.2	26.3	NG	27.5	25.0	30.8	27.6	26.2
35%										
2000	MPa	14.7	18.9	16.4	14.2	17.0	14.6	17.2	15.1	16.6
3000		16.1	21.5	19.7	20.4	21.3	19.8	24.7	21.5	20.8
4000		28.5	24.5	23.0	20.3	22.5	20.8	25.1	23.8	23.5
5000		30.0	29.1	25.9	NG	24.1	24.6	30.1	25.1	24.1
50%										
2000	MPa	11.7	18.3	13.9	9.5	11.8	11.1	14.6	11.4	13.1
3000		15.0	19.1	17.1	15.5	18.0	18.0	22.7	20.2	17.1
4000		20.6	21.4	20.9	17.8	18.8	19.7	23.9	21.6	21.1
5000		22.3	28.7	25.4	NG	19.6	23.1	26.9	24.4	22.0
70%										
2000	MPa	7.1	11.9	7.8	7.2	9.7	7.0	11.5	9.7	9.6
3000		7.9	12.8	12.1	8.5	12.8	10.5	14.5	12.5	11.7
4000		8.5	17.1	13.0	9.1	13.4	11.9	17.5	16.0	14.7
5000		10.8	19.8	16.8	NG	15.5	15.6	21.0	20.4	18.8

NOTES: 1. Portland cement meets requirements of CSA Type 10.
2. Nominal Blaine fineness of slags indicated - 2000, 3000, 4000 and 5000.
3. All compressive strengths in MPa.
4. NG indicates slag was not ground to this fineness.

*From Ref. (13).

Table 15 - Compressive strength at 23°C of "C-109" mortar cubes
50 per cent absolute volume replacement of portland cement*

		Lead (N.B.) Granulated	Nickel (Ont.) Air-cooled	Nickel (Ont.) Quenched	Copper (Ont.) Granulated	Copper (Ont.) Quenched	Copper (Que.) Air-cooled	Copper (Que.) Air-cooled	Copper (Que.) Quenched	Copper (Que.) Granulated
CONTROL	7D	31.3	31.3	31.3	31.3	31.3	31.3	31.3	31.3	31.3
	28D	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
2000										
Days 1	MPa	7.0	3.9	4.8	4.6	4.7	3.1	3.3	4.3	3.8
7		10.8	8.7	10.7	9.0	9.1	8.8	9.2	9.3	7.4
28		19.1	14.2	17.8	19.0	17.0	12.0	14.4	16.2	13.8
90		29.5	21.6	23.0	25.1	21.7	16.7	19.4	21.1	18.5
3000										
Days 1	MPa	8.5	4.0	5.0	4.9	5.0	4.7	3.3	5.0	4.0
7		12.4	8.8	10.8	10.3	11.0	10.9	9.5	12.6	8.6
28		23.5	15.6	19.3	25.7	21.8	15.7	18.0	24.6	14.3
90		37.9	26.0	26.1	29.7	26.5	20.6	25.9	32.0	24.3
4000										
Days 1	MPa	12.1	4.1	5.2	5.6	6.3	5.0	4.3	5.6	4.7
7		14.1	10.0	11.7	10.5	12.5	12.0	11.0	14.8	10.3
28		29.8	17.5	21.7	26.7	24.8	19.2	20.5	30.5	21.6
90		40.2	28.3	26.6	31.4	31.1	23.2	29.2	37.3	29.1
5000										
Days 1	MPa	14.1	4.4	7.0	NG	7.5	5.1	4.5	5.9	5.3
7		18.2	11.2	13.1		16.0	12.9	11.2	17.1	11.5
28		28.7	25.0	26.2		30.4	21.3	24.2	35.2	25.9
90		43.7	33.1	31.7		38.9	26.8	32.0	38.3	32.8

NOTES: 1. Portland cement meet requirements of ASTM "Specifications for Ground Blast-Furnace Slag for Use in Concrete and Mortars" as developed by E38.06.02. (Peerless cement intermediate between Type 1 and Type 2.)
2. Nominal Blaine fineness of slags indicated - 2000, 3000, 4000 and 5000.
3. All compressive strengths in MPa, with flow indicated for each mix.
4. NG indicates slag was not ground to this fineness

*From Ref. (13).

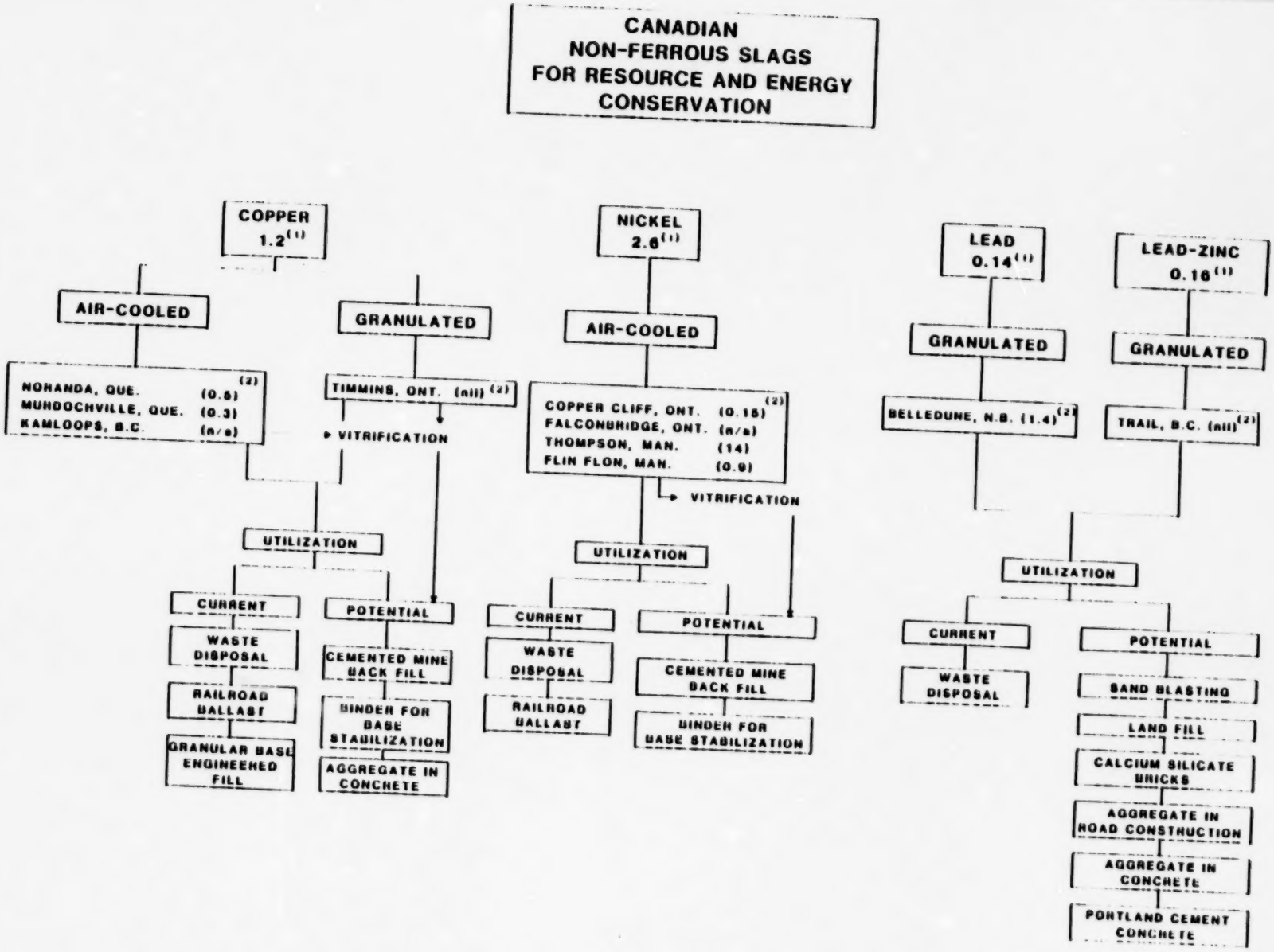


Fig. 1. Production, location and utilization of non-ferrous slags from Canadian sources. From Ref. (7).

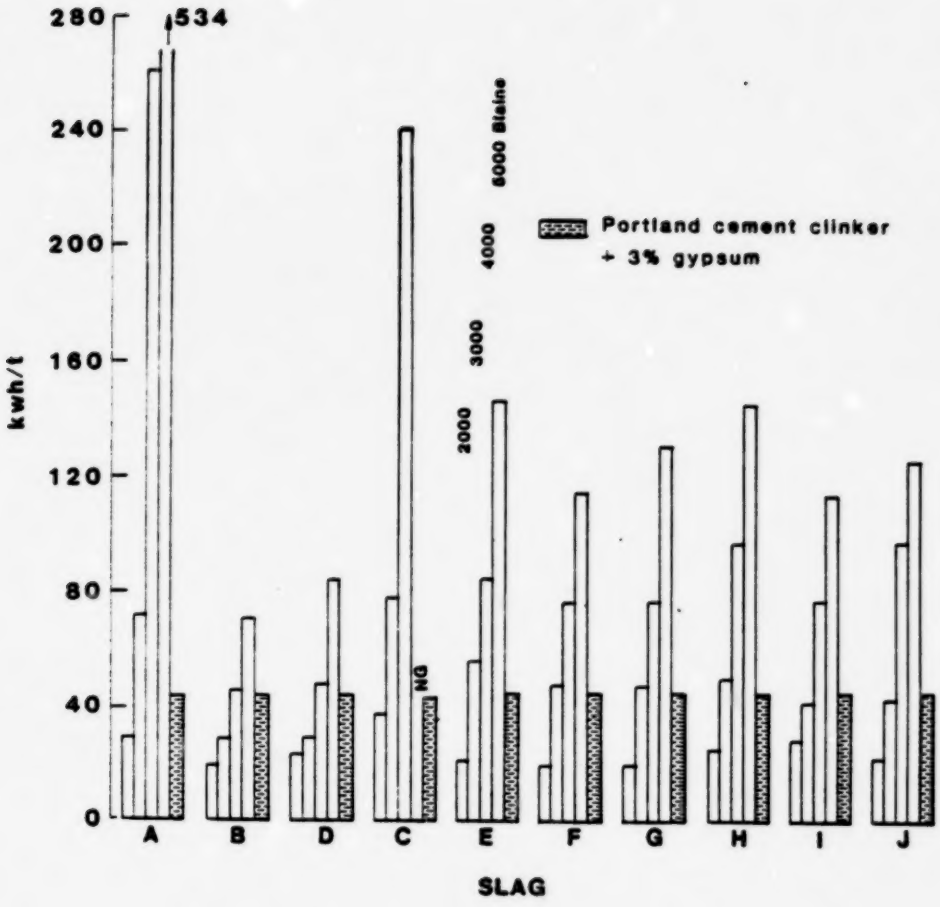


Fig. 2. Comparison between the energy required to grind portland cement clinker and non-ferrous slags. From Ref. (13).

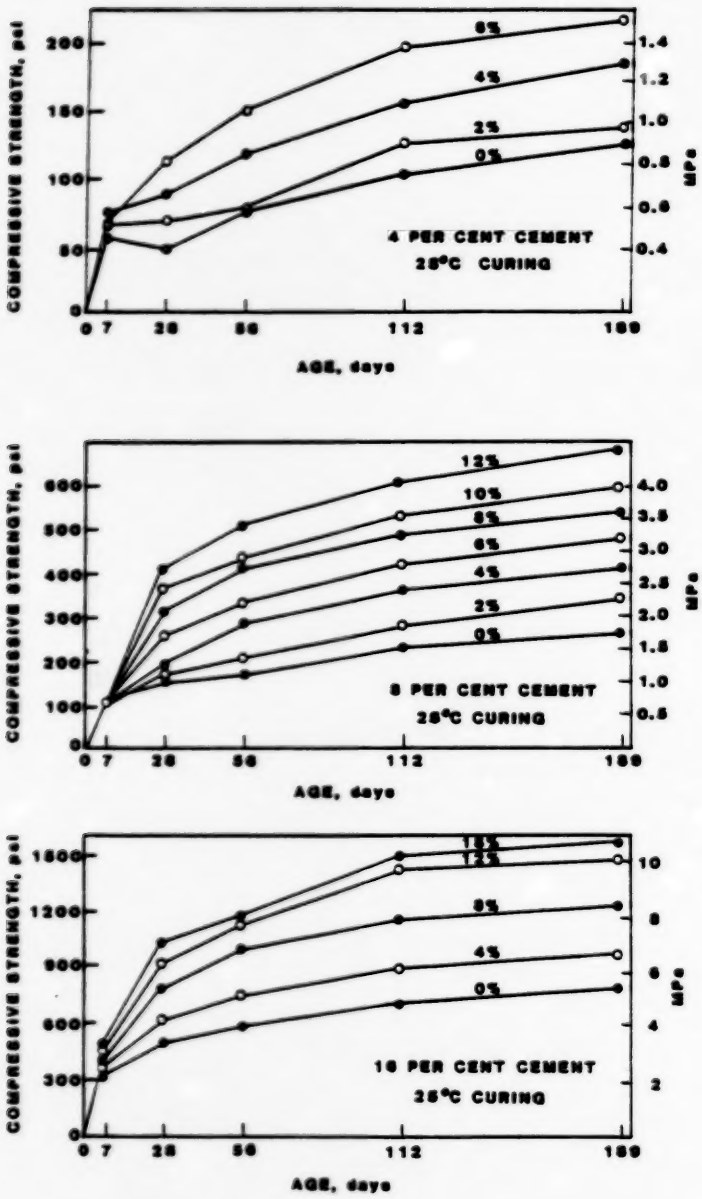


Fig. 3. Curing curves demonstrating strengthening effect of ground copper reverberatory furnace slag acting as a pozzolan with different cement contents. From Ref. (9).

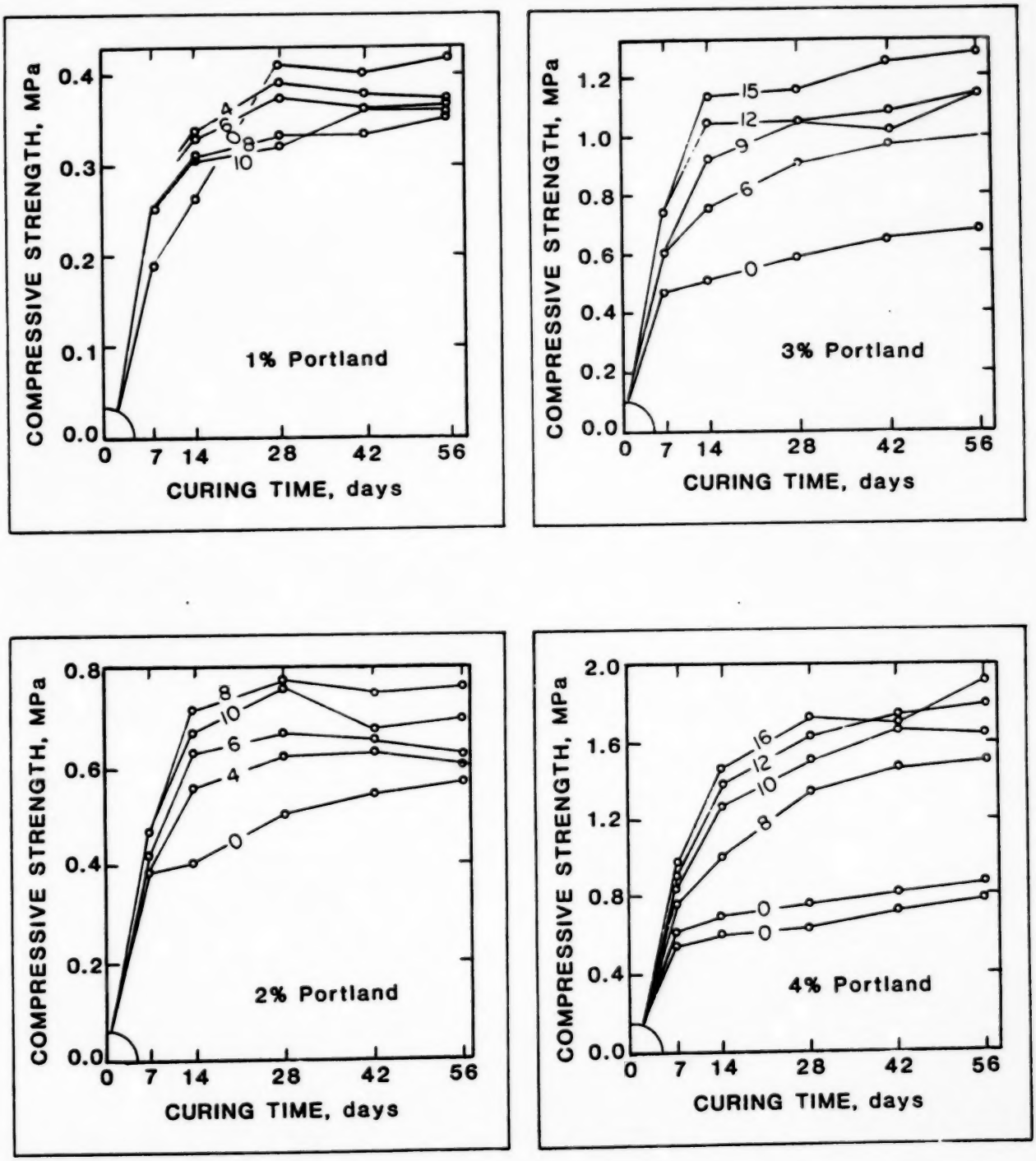


Fig. 4. Curing curves at 1, 2, 3 and 4 wt per cent portland cement and various copper reverberatory furnace slag additions, as indicated on individual curves. From Ref. (10).

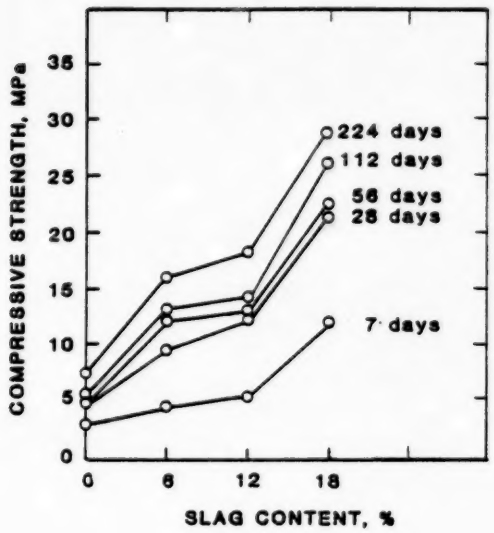


Fig. 5. Effect of ground granulated slag on uniaxial compressive strength of consolidated fill containing 6 per cent portland cement. From Ref. (14).

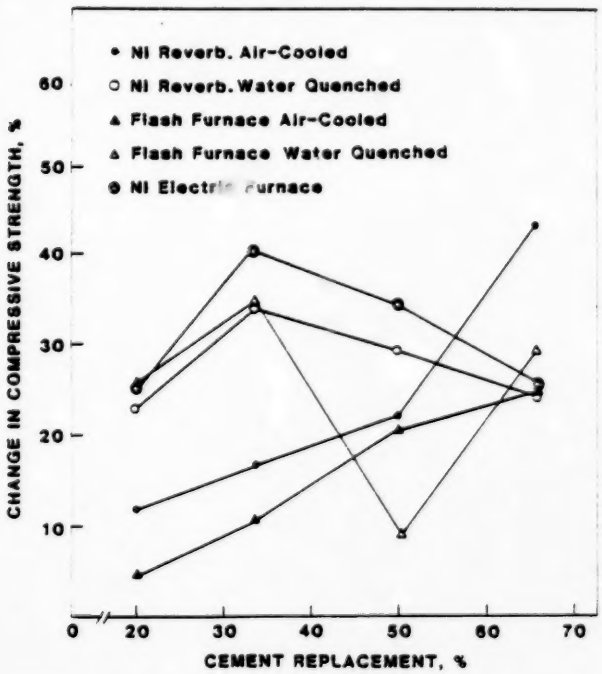


Fig. 6. Change in strength at different curing ages calculated on basis of standard 4.8 wt per cent portland cement specimens cured to same age during pozzolanic test at various cement replacement levels. From Ref. (21).

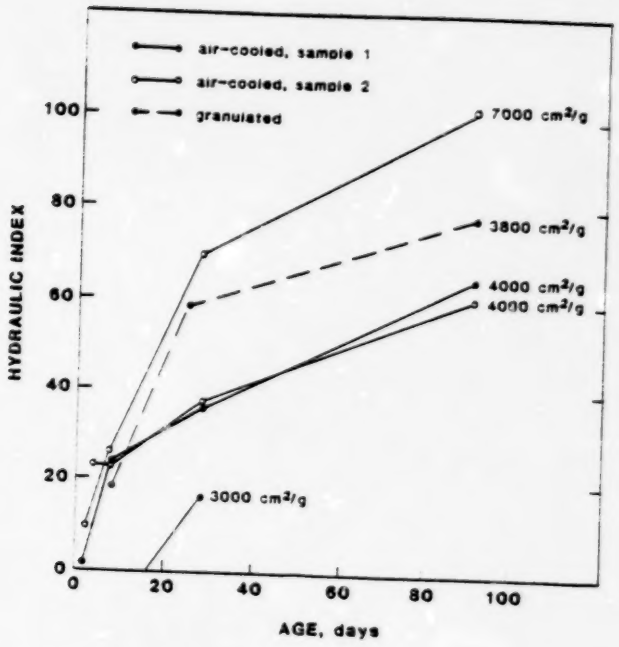


Fig. 7. Hydraulic index of air-cooled and of granulated nickel slags of different fineness. From Ref. (11).

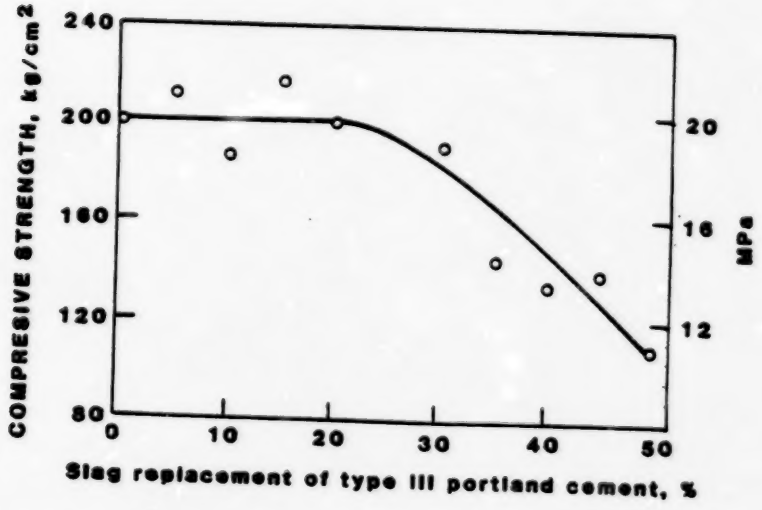


Fig. 8. Compressive strength of Type III portland cement-lead slag binders at various cement replacement levels. From Ref. (24).

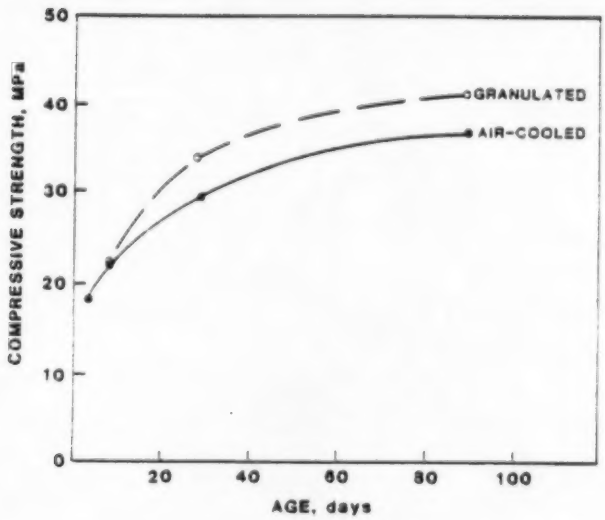


Fig. 9. Effect of water quenching on strength development of nickel slags. From Ref. (11).

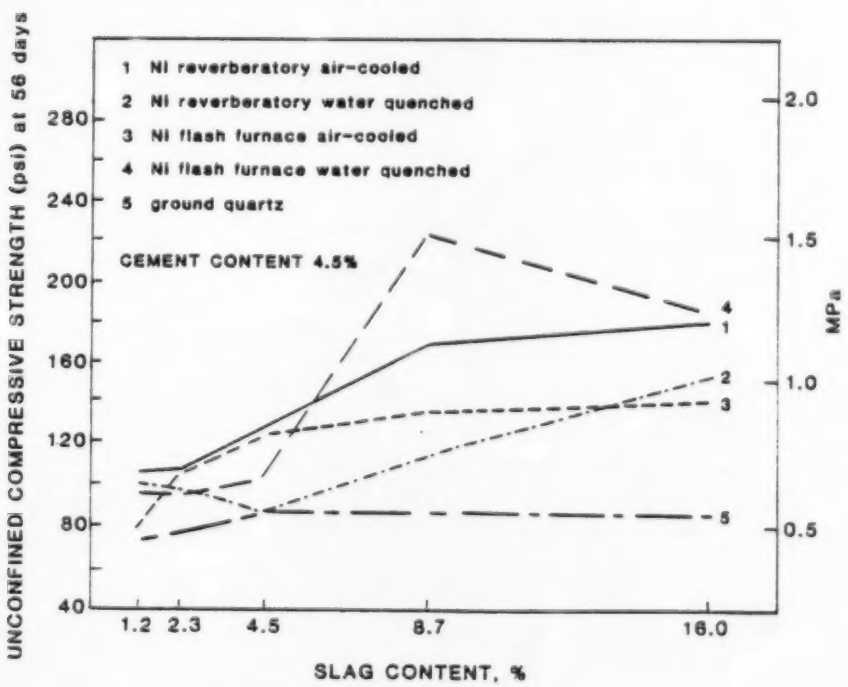
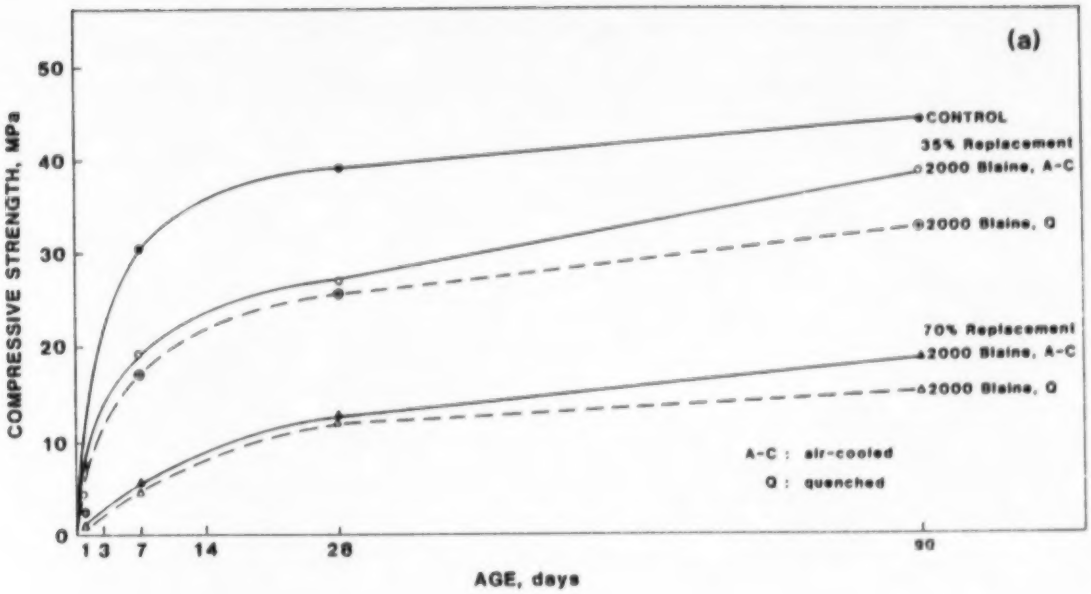


Fig. 10. Unconfined compressive strength at 56 days of air-cooled and water quenched nickel slags. From Ref. (23).



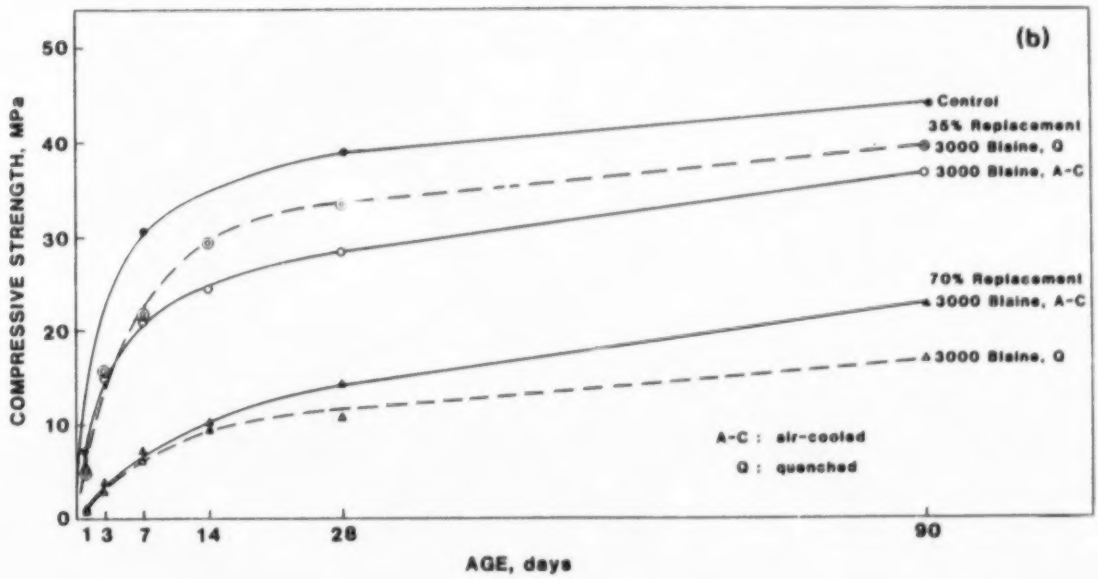
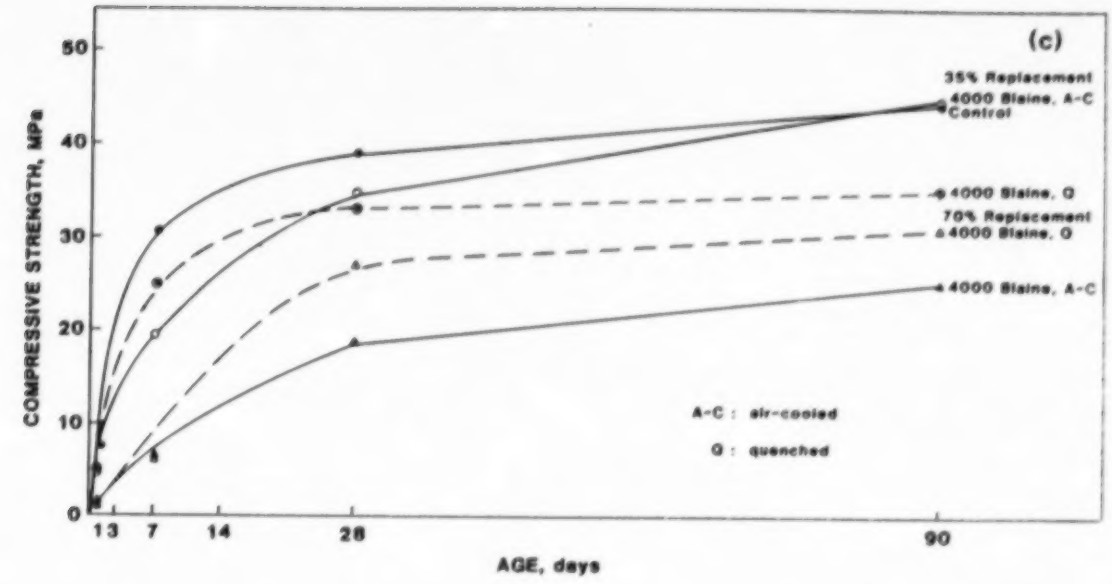


Fig. 11(a,b). Strength development in portland cement-copper slag mortars cured at room temperature. From Ref. (17).



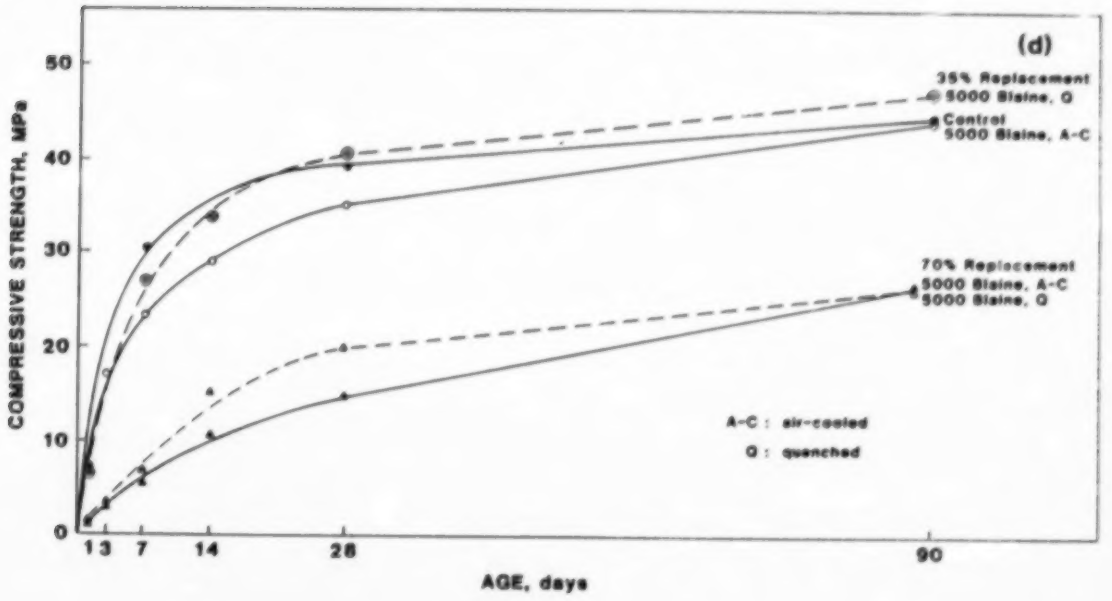


Fig. 11(c,d). Strength development in portland cement-copper slag mortars cured at room temperature. From *Ref.* (17).

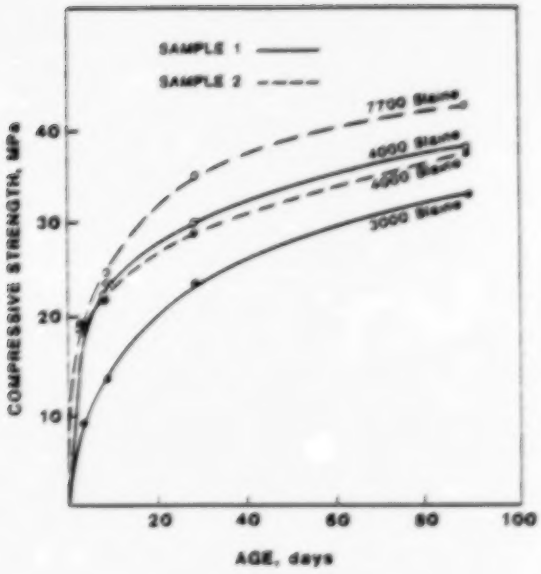


Fig. 12. Effect of fineness on compressive strength of 70 wt per cent portland cement and 30 wt per cent air-cooled nickel slag binders. From Ref. (11).

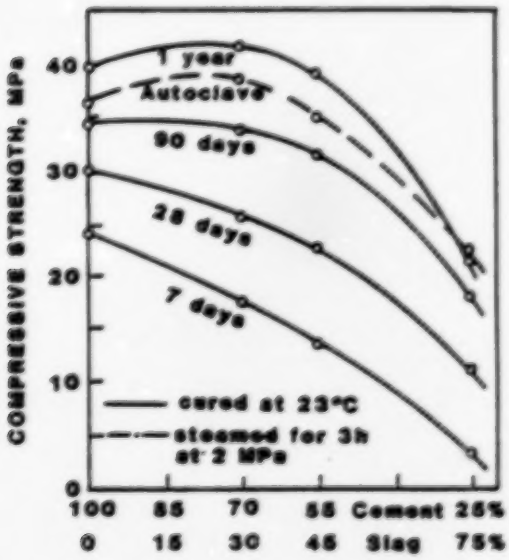


Fig. 13. Effect of slag content of binders on the compressive strength of ASTM C-109 mortars cubes. From Ref. (26).

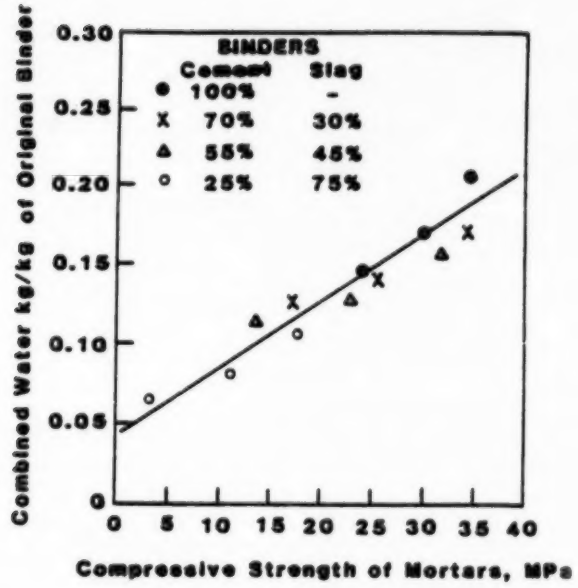


Fig. 14. Relation between combined water and compressive strength. From Ref. (26).

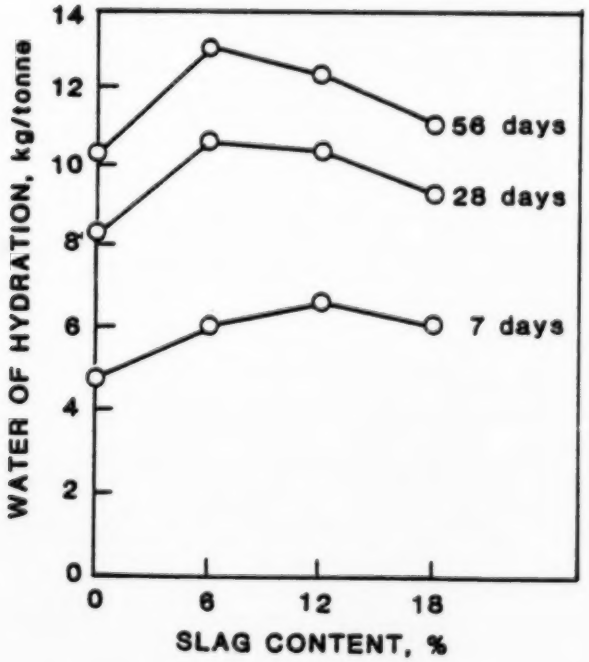


Fig. 15. Effect of ground granulated slag on hydration in consolidated fill containing 6 per cent portland cement. From Ref. (14).

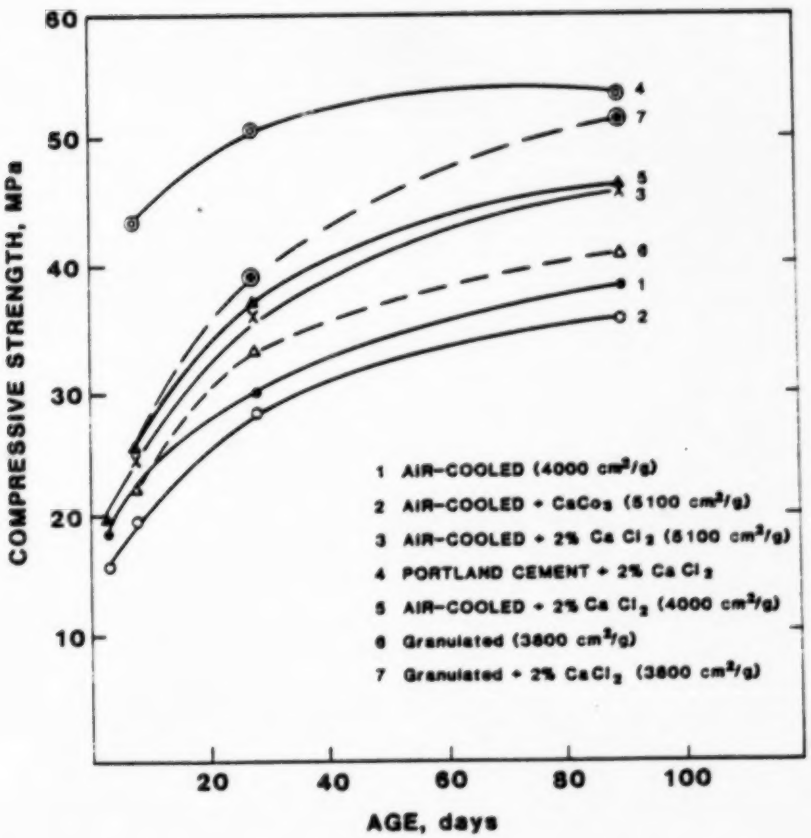


Fig. 16. Effect of activators on compressive strength of air-cooled and granulated nickel slags ground to various fineness. From Ref. (11).